HIGH EFFICIENCY CARBONATE FUEL CELL/TURBINE HYBRID POWER CYCLES

SECOND WORKSHOP ON VERY HIGH EFFICIENCY FUEL CELL/ADVANCED TURBINE POWER CYCLES

FUEL CELLS 96 -- MORGANTOWN ENERGY TECHNOLOGY CENTER

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INTRODUCTION - There are strong incentives for systems that produce electric power at very high efficiency. The incentives are conservation of natural resources, reduced emissions, and lower cost of electricity as fuel costs escalate.

Energy Research Corporation (ERC) has conducted studies of hybrid power cycles in cooperation with the U.S. Department of Energy, Morgantown Energy Technology Center (METC) to identify a higher efficiency, economically competitive system. The basis of these studies is the direct carbonate fuel cell being developed by ERC which can generate power at an efficiency approaching 60% LHV. This unique fuel cell technology can consume natural gas and other hydrocarbon based fuels directly without requiring an external reformer, thus providing a simpler and inherently efficient power generation system. A 2 MW power plant demonstration of this technology has been initiated at an installation in the city of Santa Clara in California. A 2.85 MW commercial configuration, shown in Figure 1, is presently being developed. The plant includes the carbonate fuel cell modules, an inverter, transformer and switchgear, a heat recovery unit and supporting instrument air and water treatment systems. The emission levels for this 2.85 MW plant are projected to be orders of magnitude below existing or proposed standards. The 30 year levelized cost of electricity, without inflation, is projected to be approximately 5¢/kWh.

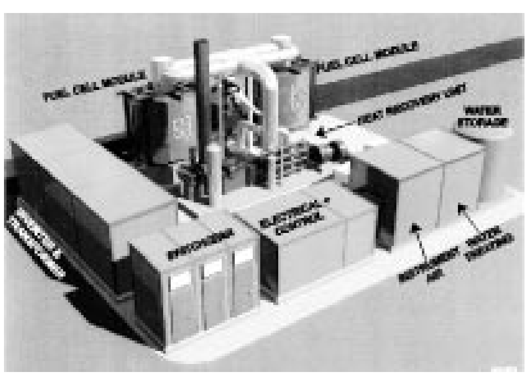

Figure 1. 2.85 MW POWER PLANT:
The Direct Fuel Cell Technology
for the Hybrid Cycle

HYBRID POWER CYCLE DESCRIPTION - The hybrid power cycle system shown in Figure 2 includes a direct carbonate fuel cell, a gas turbine, and a steam cycle. Natural gas flows to the fuel cell and the gas turbine. Air flows to the gas turbine and exhaust from the gas turbine flows to the fuel cell. Anode exhaust from the fuel cell is oxidized providing heat to the gas turbine. Cathode exhaust from the fuel cell flows to the steam cycle.

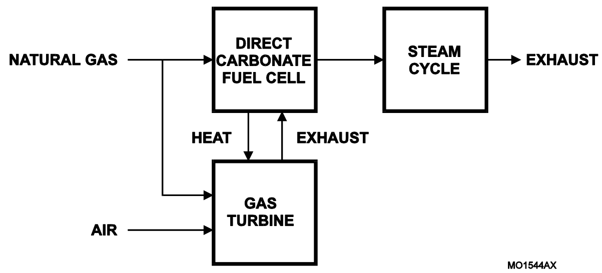

Figure 2. HYBRID POWER CYCLE:
A Topping Cycle and a Steam Bottoming Cycle are added to the Fuel Cell

Studies of a hybrid power cycle have been conducted for a 200 MW application and for a 20 MW near term application. In addition, the 3 MW commercial configuration of the direct carbonate fuel cell system has been studied with a steam bottoming system, with a gas turbine topping system, and with the hybrid power cycle. The performance of the hybrid power cycle was analyzed using CHEMCAD[2] system simulation software with an ERC developed fuel cell model. Advantages of the hybrid power cycle are:

- competitive cost
- high efficiency
- low emissions
- insensitivity to ambient temperature

Initial studies concentrated on large (200 MW) power plants to take advantage of large turbine systems. Subsequently, smaller and simpler plants were configured for more near term application. These studies are discussed below.

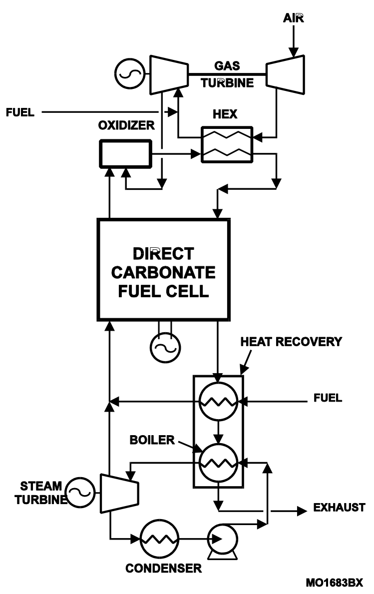

Figure 3. SYSTEM SCHEMATIC OF HYBRID POWER CYCLE:
Fuel Cell Waste Heat is Utilized by Heat Engines to Improve Efficiency

HYBRID POWER CYCLE FOR 200 MW APPLICATIONS - A hybrid power cycle at 200 MW size which generates power at an LHV efficiency in excess of 70% was studied[1] utilizing an atmospheric pressure direct carbonate fuel cell. In this study the hybrid power cycle had an LHV efficiency of 72.6% which was achieved by using a high temperature heat exchanger to transfer fuel cell waste heat to the turbine. In order to achieve the 72% efficiency potential of the hybrid power cycle, technology and development advancements are needed for heat exchangers capable of 1094°C and pressures up to 400 psig. In addition, an anode recycle at 650°C is required. This system was described at the first METC workshop on Very High Efficiency Fuel Cell/Advanced Turbine Power Cycles.

HYBRID POWER CYCLE FOR 20 MW APPLICATIONS - A near term, simplified 20 MW power plant was also studied. In this system, shown in Figure 3, a lower temperature heat exchanger (761°C) is used to transfer fuel cell waste heat to the gas turbine. This allows the use of more conventional heat exchanger technology which reduces cost and makes it possible to build this plant sooner. Methane is internally reformed in the fuel cell at an H_2O/C ratio of 1.5, and fuel utilization in the fuel cell anode is 80%.

The unreacted H_2 and CO flow to an oxidizer which operates at 761°C. Additional methane fuel is compressed and flows to the gas turbine combustor. The gas turbine compressor delivers air at 10 atm to a heat exchanger which heats the air to 589°C. The heated air then flows to the gas turbine combustor where it is heated further to 982°C before flowing through the turbine. Turbine exhaust containing O_2 and CO_2 flows to the anode exhaust oxidizer. Exhaust from the anode exhaust oxidizer heats the compressed air in the heat exchanger before being recycled to the fuel cell cathode. Exhaust from the cathode at 670°C flows to the steam bottoming system. The steam bottoming system includes a Heat Recovery Steam Generator (HRSG), steam turbine, condenser and condensate and boiler feed pumps. The steam turbine includes an extraction point for the steam to the fuel cell system. The HRSG includes a reheater for the fuel cell system steam, a superheater, and a boiler. The system also includes a condensate reheater and deaerator, not shown on the simplified schematic. Exhaust leaves the system to the atmosphere at 62°C.

Performance of the 20 MW hybrid system is summarized in Table 1. Sixty-five percent of the power is produced by the fuel cell system, 16 % comes from a generator driven by the gas turbine, and the remaining 19% comes from the generator driven by the steam turbine. There is a 4% loss for pumps and blowers in the system. The overall efficiency of the hybrid power cycle is 65.2% (LHV).

Table 1. 20 MW HYBRID POWER CYCLE PERFORMANCE:
Overall Efficiency is 65%

	MW
POWER GENERATION	
Gas Turbine	3.5
Fuel Cell	14.3
Steam Turbine	4.1
Parasitic Power	-0.8
TOTAL	21.1
NET AC LHV EFFICIENCY	%
Fuel Cell	57.2
Fuel Cell & Gas Turbine	52.6
Steam System	35.7
Overall	65.2

COST OF ELECTRICITY - The 30 year levelized cost of electricity for the 20 MW plant with a hybrid power cycle is estimated at 5.1 ¢/kWh, without inflation, using methods recommended by EPRI TAG[4]. This includes levelized plant cost of 1.4 ¢/kWh, operating and maintenance (O&M) cost of 1.3 ¢/kWh, and levelized fuel cost of 2.4 ¢/kWh.

The 30 year levelized plant cost is based on overall capital cost of $1059/kW in 1995 dollars. This overall plant capital cost assumes $1000/kW for the fuel cell system. The capital cost for the gas turbine was estimated at $610/kW[5] and the steam system at $1260kW[5].

The O&M cost includes the fuel cell system O&M cost projected by ERC at 0.8 ¢/kWh including 5 year stack replacement. The combined O&M costs for the gas turbine and steam system is estimated at 0.5 ¢/kWh[3]. The levelized fuel cost of 2.4 ¢/kWh is based on a first year fuel cost of $3/MMBTU ($3.163/MMKJ) and a capacity factor of 0.91. The calculated levelizing factor is 1.37[4], an interest rate of 5.3%, no inflation and a fuel escalation rate of 2.5% per year.

COMPARISON WITH A 20 MW GAS TURBINE COMBINED CYCLE - For perspective on the commercialization prospects for a 20 MW hybrid power cycle, a comparison was made with a 20 MW gas turbine combined cycle. The comparison addressed issues of performance, emissions and cost of electricity. The gas turbine combined cycle selected for the comparison is a commercially available model rated at 18.7 MW. This system is composed of a single gas turbine rated at about 13.4 MW and a 5.3 MW steam turbine. The published[5] heat rate is 6870 BTU/kWh (49.7% LHV efficiency). The 30 year levelized cost of electricity for the 20 MW class combined cycle was estimated at 5.2 ¢/kWh, without inflation, using EPRI TAG[4]. The 30 year levelized plant cost is based on published [5]cost of the commercially available model combined cycle, and estimates of installation and project cost, resulting in an estimated plant capital cost of $954/kW. The O&M cost[3] of the combined cycle is in 1995 dollars. The levelized fuel cost of 3.1 ¢/kWh is based on the same assumptions as used to estimate the fuel cost for the hybrid power cycle. A breakdown of cost of electricity is shown in Table 2 in comparison with the hybrid power cycle. As shown in Table 2, the hybrid power cycle COE fuel cost component at $3/MMBTU is significantly less than the fuel cost component for the combined cycle, off-setting the higher plant and O&M COE cost components in the hybrid power cycle. As first year fuel costs increase, the COE cost advantage of the hybrid system increases, as shown in Figure 4. The hybrid power cycle is competitive with the combined cycle for 20 MW installations in which the first year fuel cost is above $2.5/MMBTU.

Table 2.
HYBRID POWER CYCLE VS. COMBINED CYCLE LEVELIZED COE

	Hybrid Power Cycle ¢/kWH	Combined Cycle ¢/kWH
Fuel	**2.38**	**3.13**
Plant	**1.36**	**1.20**
O&M	**<u>1.31</u>**	**<u>0.83</u>**
Total	**5.05**	**5.16**

EMISSIONS - A comparison between the NO_x emissions of a hybrid power cycle and a gas turbine combined cycle was made on the basis of equilibrium levels predicted from the burners in the two systems at their respective operating conditions. The results showed that the 20 MW hybrid power cycle is expected to generate 83% less NOx than a 20 MW gas turbine combined cycle.

The emission of sulfur dioxide (SO_x) is expected to be only about 1% of the level from a gas turbine combined cycle because the fuel is desulfurized in the process. The contribution of carbon dioxide CO_2 to the atmosphere is expected to be about 24% lower than a gas turbine combined cycle due to the higher efficiency. The over-all result is significantly lower emissions for the hybrid power cycle.

3 MW DIRECT FUEL CELL WITH STEAM BOTTOMING CYCLE - One approach to achieving an efficiency higher than the 57% expected for the 2.85 MW commercial configuration of the direct carbonate fuel cell system is to add a steam bottoming cycle. A schematic of this system approach is shown in Figure 5. The fuel cell cathode exhaust at 677°C flows to a heat recovery steam generator, HRSG where steam is raised. About 35% of the steam flows to the fuel cell where it is used in the steam reforming process within the carbonate fuel cell stacks. The remaining steam flows to a steam turbine/generator. Exhaust from the steam turbine is condensed and recycled back to the boiler. Water make up in the system is needed to offset the steam used in the fuel cell system.

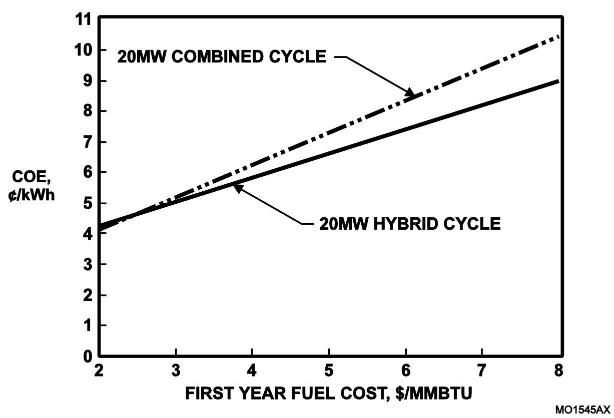

Figure 4. EFFECT OF FIRST YEAR FUEL COST ON COST OF ELECTRICITY: Hybrid Cycle Provides Significant Advantage at High Fuel Costs

In studies of this system, two steam turbine configurations were considered. In one configuration the steam expands through a single stage non-condensing turbine to a pressure level of about 20 psia. Thirty-five percent of the steam flows to the fuel cell and the remainder is condensed and recycled. In the other configuration studied, the remaining steam at 20 psia flows to a condensing turbine where it expands to 0.7 psia (32°C) before being condensed. For simplicity in this small steam plant size, no reheat of the 20 psia steam was included as in the system for 20 MW near term application described above. The efficiency of the carbonate fuel cell with steam bottoming is shown in Figure 6. The total system efficiency is shown as a function of the steam bottoming system configuration and steam conditions of pressure and superheat temperature. Also shown on Figure 6 is the power output of the steam turbine at discreet points. With steam bottoming, the direct carbonate fuel cell can deliver power at an efficiency of 63% to 65.5% depending on the configuration and conditions of the steam bottoming system.

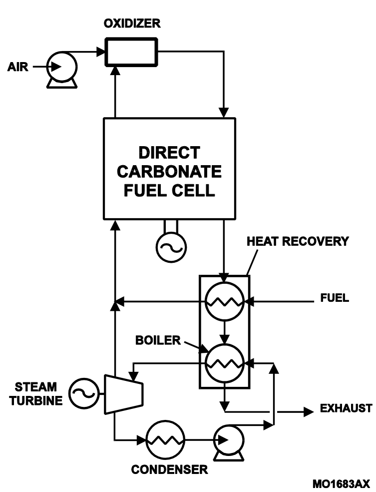

Figure 5. 3 MW SYSTEM WITH STEAM CYCLE: Fuel Cell Waste Heat is Utilized to Improve Efficiency

3 MW DIRECT FUEL CELL WITH GAS TURBINE TOPPING - Another approach to achieving an efficiency higher than the 57%

expected for the 2.85 MW commercial configuration of the direct carbonate fuel cell system is to include a gas turbine topping cycle as shown in Figure 7. In the topping cycle, air from the gas turbine compressor flows through a heat exchanger where it is heated to about 1400°F. The heated air then flows to the gas turbine burner where a small amount of raw fuel is burned raising the stream to about 1600°F before expanding through the turbine. The turbine exhaust flows to the fuel cell anode exhaust oxidizer. Exhaust from the anode exhaust oxidizer flows to the heat exchanger which provides the heat for the compressor air. The exit from the heat exchanger flows through the fuel cell cathode providing the oxygen and carbon dioxide needed in the carbonate fuel cell process. The efficiency of the carbonate fuel cell with gas turbine topping is shown in Figure 8 as a function of the total power delivered.

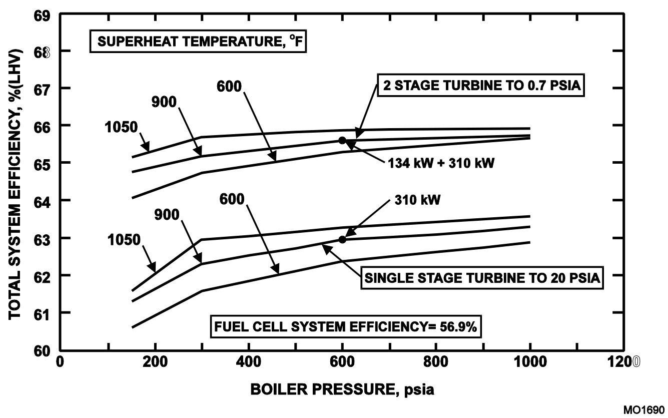

Figure 6. 3 MW DIRECT FUEL CELL WITH STEAM BOTTOMING:
A 2 Stage Steam Turbine can Raise Efficiency Above 65%

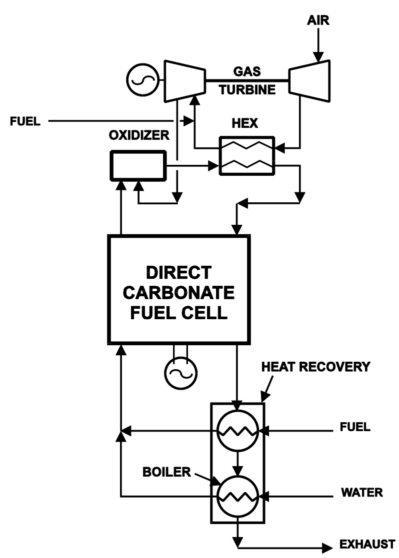

Figure 7. CARBONATE FUEL CELL WITH TOPPING CYCLE:
Over 61% Efficiency can be Achieved

3 MW DIRECT FUEL CELL WITH GAS TURBINE TOPPING AND STEAM BOTTOMING - The hybrid power cycle in 3MW size combines both the topping and bottoming cycle as shown in Figure 3. The efficiency breakdown for the hybrid power cycle for a 3 MW plant is shown in Figure 8 as a function of the power generated. The basic fuel cell efficiency of 57% is shown as well as the efficiency with just the topping cycle and with the combined topping and steam bottoming system for the two versions of the steam bottoming cycle previously discussed. The peak efficiency achievable is about 69%.

ECONOMICS OF IMPROVED EFFICIENCY - An important issue in developing advanced high efficiency systems is the comparative economics of adding additional system complexity to achieve higher efficiency. The question is, does the efficiency benefit offset the added capital cost?

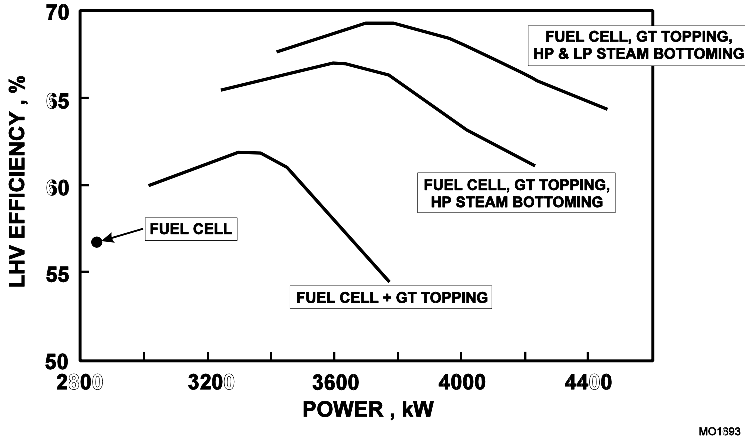

Figure 8. 3 MW DIRECT FUEL CELL WITH GAS TURBINE TOPPING & STEAM BOTTOMING: Efficiency of 69% can be Achieved

To answer this question, a preliminary study was conducted to establish a break-even cost for the added equipment (i.e., the value of the added equipment in terms of fuel savings). The projected 30 year levelized cost of electricity for the 2.85 MW carbonate fuel cell commercial configuration is shown in Table 3. Fuel cost at 57% efficiency is estimated at 2.7 ¢/kWh based on a fuel cost of \$3/MMBTU. Plant cost is estimated at 1.3 ¢/kWh based on assumed capital cost of \$1000/kW. A break-even cost for added equipment in the steam bottoming system and the gas turbine topping cycle was established as the cost saving from the reduced fuel cost at higher plant efficiencies. The break-even cost for the steam bottoming system is shown in Figure 9. The break-even cost of the steam bottoming equipment is between \$2200/kW and \$4000/kW, depending on fuel cost. This represents the value of the steam system in dollars per kilowatt of power generated by the steam system.

Table 3. LEVELIZED COE:
3 MW Fuel Cell System

1995 \$, Without Inflation

	Levelized Cost, ¢/kWh
Fuel (@ \$3/MMBtu)	2.7
Plant	1.3
O&M	1.2
TOTAL	**5.2**

By comparison, the break-even cost of the gas turbine topping cycle equipment is between \$1500/kW and \$2300/kW, depending on fuel cost, as shown in Figure 10. Typical cost for a small gas turbine generator is shown in Figure 11. In the range of interest for a topping unit with a 3 MW fuel cell the gas turbine would provide about 400 to 1000 kW. In this range the cost is expected to be about \$1000-1200/kW. Additional equipment required for the topping cycle includes the heat exchanger and a blower.

RESEARCH AND DEVELOPMENT NEEDS FOR HYBRID POWER SYSTEMS - Studies of the hybrid power cycle have established the expected efficiency in plant sizes of 200 MW, 20 MW and 3MW. Initial emphasis on a 3-10 MW system is recommended to limit the cost of initial system demonstration. To advance the hybrid power cycle concept further, more detailed system integration and optimization studies with turbine vendor participation are needed. More detailed study is needed to minimize complexity and maximize reliability and to define the operational aspects of start-up, transients, off-design operating conditions and supporting balance of plant equipment and utilities.

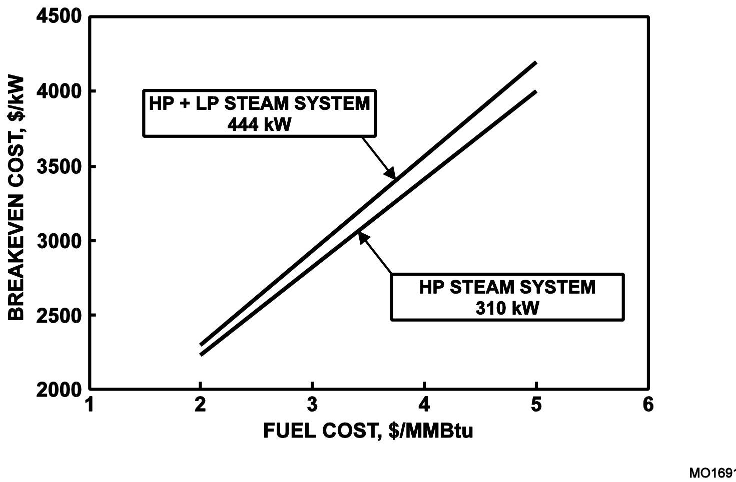

Figure 9. VALUE OF STEAM BOTTOMING CYCLE FOR 3 MW POWER PLANT:
The Steam Bottoming Cycle has a Value of $2200/kW at $2/MMBTU Fuel Cost

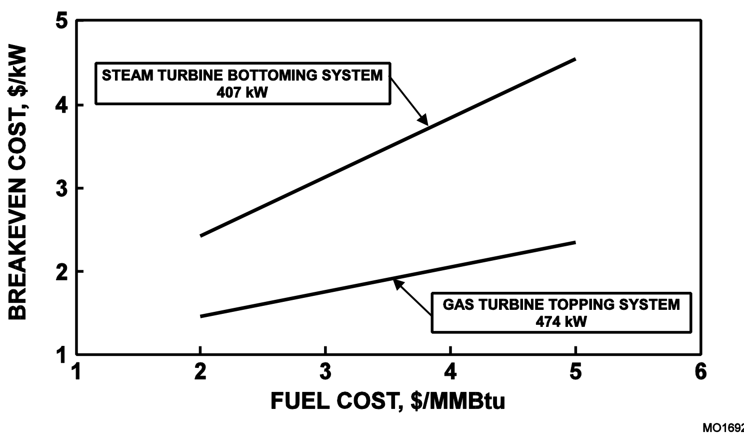

Figure 10. VALUE OF TOPPING & BOTTOMING CYCLE FOR 3 MW POWER PLANT:
A Bottoming Cycle has Higher Value

In particular, it is necessary to identify small, efficient, low cost steam and gas turbine systems. Interface details between the fuel cell and turbine systems must be established. Although higher efficiency has environmental advantages, more detailed economics must also be developed to establish the cost of electricity incentive for the higher efficiency under various fuel cost scenarios.

Demonstration testing is needed on fuel cell stacks to confirm performance expectations at hybrid cycle conditions, on the small turbines at their respective hybrid cycle conditions, and on a 3-10 MW total system to validate the system integration and characteristics for commercialization.

CONCLUSIONS - A 20 MW hybrid power cycle for near term application using available technology, including a 760°C heat exchanger, with steam provided from the bottoming cycle steam system rather than anode recycle result in an estimated (unoptimized) LHV efficiency of 65%. The NO_x emissions are 83% lower than a 20 MW gas turbine combined cycle. The estimated cost of electricity for the near term 20 MW plant with a hybrid power cycle is 5.1 ¢/kWh, which is competitive with a 20 MW combined cycle for installations where the fuel cost is above $2.5/MMBTU.

At 3-4MW scale, the atmospheric pressure direct carbonate fuel cell system can achieve optimum efficiencies approaching 70% (LHV) when integrated with steam and gas turbines in a hybrid cycle system.

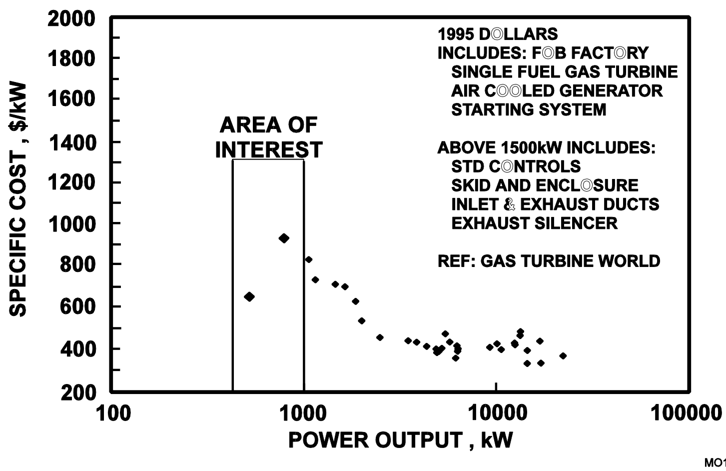

Figure 11. GAS TURBINE SYSTEM COST:
Limited Data in Size of Interest

Efficiencies approaching 65% (LHV) are achievable when integrating the fuel cell with just a steam bottoming system. A steam system costing less than $2300/kW is economically competitive for applications where the fuel cost is $2/MMBtu.

Research and development needs to realize this potential include further studies with turbine vendor participation to confirm and optimize performance and cost projections and establish system interfaces. In addition, demonstration testing is required to validate system integration and characteristics for commercialization.

ACKNOWLEDGEMENT:

This study was conducted in part in cooperation with the U.S. DOE Morgantown Energy technology Center under CRADA 93-014.

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